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CONSIDERATION OF DESIGN SYSTEMS FOR SOLAR POWERED REVERSE OSMOSIS SEAWATER DESALINATION

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ABSTRACT

Solar-powered reverse osmosis (RO) seawater desalination systems are one of the best solutions for providing fresh, clean water. This paper presents research concerning solar-powered reverse osmosis (RO) seawater desalination. The research consists of a review of solar-powered RO desalination, previous designs of solar-powered RO seawater desalination systems, and a design of a solar-powered RO seawater desalination system in Durban. The review includes solved issues regarding the cost and efficiency of the RO seawater desalination system. The review also focuses on how to make the RO desalination portable and how to improve the RO system processes. The main aim and objective of this research was to conduct research on previous findings regarding solar-powered RO seawater desalination, and to propose a design system that will provide a reasonable amount of water for the community of Durban. The proposed design system produces 16 830 000 L of water per year using solar energy with super-capacitors and battery as a power source. The solar powered RO seawater desalination systems can be improved by having a two-stage RO process, and by having three energy sources (solar energy, battery/capacitor, and wind energy) in order to increase freshwater produced per annum. Although having a battery in a system creates energy losses and batteries are a reliable source of energy.

KEYWORDS: Desalination, RO, Solar-Powered & Solar Energy

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NOMENCLATURE

Variable	Description/Name	Units
RO	**Reverse osmosis**	**none**
x_1	Number of pressure vessels in pre-treatment system	dimensionless
x_2	Number of RO membrane modules per pressure vessel	dimensionless
x_3	Selected RO membrane module type from catalogued list	dimensionless
x_4	Nominal salty water intake flow rate	m^3/hr
x_5	Nominal operating pressure for the high-pressure pumps	bar
x_6	Ratio of the nameplate DC power of the PV panels to the maximum operating power of the RO system	kW/kW
x_7	Ratio of the battery storage capacity to the maximum operating power of the RO system	kW.hr/kW
x_8	Proportional constant for power dispatch controller	dimensionless
x_9	Derivative constant for power dispatch controller	hr
x_{10}	Number of pressure vessels in the RO membrane	dimensionless
x_{11}	Nominal feed water (from the pre-treatment system into the RO membrane) flow rate	m^3/hr
$f_1(x)$	Equivalent cost per day of the whole system	Rands
$f_2(x)$	Average daily freshwater production	m^3
$f_3(x)$	Inlet salty water flow rate into a single pressure vessel of the pre-treatment system, at nominal maximum flow rate and pressure conditions	m^3/hr
$f_4(x)$	Maximum allowable flow rate per RO membrane module	m^3/hr
$f_5(x)$	Exiting brine flow rate from a single pressure vessel of the RO rack, at	m^3/hr

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	nominal maximum flow rate and pressure conditions	
$f_6(x)$	Minimum permissible flow rate per RO membrane module	m^3/hr
$f_7(x)$	Freshwater flow rate from the first RO membrane module in a pressure vessel, at nominal maximum flow rate and pressure conditions	m^3/hr
$f_8(x)$	Discharged brine pressure at the exit from the pressure vessel (inlet to the pressure exchanger)	bar
$f_{10}(x)$	Inlet feedwater flow rate into a single pressure vessel of the RO membrane, at nominal maximum flow rate and pressure conditions	m^3/hr
η_r	Energy recovery efficiency of the pressure exchanger	dimensionless
η_p	Combined efficiency factor to account for the pumping station hydraulic efficiency, as well as motor and transmission	dimensionless
η_B	Battery charging efficiency	dimensionless
n_v	Number of pressure vessels that are operated	dimensionless

1. INTRODUCTION

The shortage of freshwater has become a global crisis, with global warming coming into play. As the population increases, there is a high demand for freshwater. Most of the Earth is made up of water, specifically seawater. Seawater is not friendly to human beings. Solar-powered reverse osmosis (RO) seawater desalination is one of the solutions used to produce freshwater using seawater. Solar energy is used to minimize the cost of the system, thus, reducing the cost of freshwater produced. Furthermore, solar energy is eco-friendly. Solar-powered RO seawater desalination systems have photovoltaic (PV) solar panels, reverse osmosis membranes, and a pre-treatment system. There have been many pieces of research on solar-powered RO seawater desalination systems. Research is ongoing to improve the system and to make the RO desalination system more efficient at a low cost.

2. A REVIEW OF SOLAR-POWERED RO SEAWATER DESALINATION SYSTEMS

Riffel et al. [1] conducted research on the Brazilian experience with a photovoltaic (PV) powered reverse osmosis plant. The research was based on two strategies: firstly, the PV-RO plant was equipped with a DC motor, and secondly, the plant used a three-phase induction motor. Analysis of results showed that the second option was the better alternative because it had a recovery ratio of 27 %, a specific electrical consumption of 3.03 kWh/m^3, and a drinking water cost of 12.76 US dollars per m^3. Abdallah et al. [2] focused on the performance of a PV powered RO system under local climatic conditions. In order to study the effect of tracking on the system's performance, a one-axis east-west tracking flat-plate PV was constructed. The results showed that a gain of 25 % and 15 % of electrical power and water flow could be achieved using the one-axis east-west tracking system as compared to a fixed flat plate.

Shaefer and Richards [3] tested a hybrid membrane system for groundwater desalination in an Australian national park. The hybrid membrane system had two membranes operated with different operation pressures. These membranes were tested with regards to power, energy consumption, flux, recovery and retention. Results obtained revealed that the specific energy consumption was below 5 W.h/L when operated at pressure above 7 bar, and retention of multivalent ions was stable at > 98 % whereas the retention of monovalent ions varied between 88 % and 95 % depending on the system's pressure, with a maximum between 7 bar and 10 bar. Prihasto et al. [4] investigated different pre-treatment strategies for seawater desalination by RO. The investigation showed that pre-treatment strategies to prevent membrane fouling and to extend the life cycle of the RO membrane could be categorized into conventional and non-convectional. They concluded that both these strategies could be applied to the system, but they are highly dependent on site and depend on the type of

feed water. Asher et al. [5] designed and cost analysed a solar PV powered RO plant for Masdar Institute. The system reduced greenhouse gas emissions by 1.035 tCO_2 annually. Results obtained showed the benefit-cost ratio to be 0.72, and the equity payback time to be 23.3 years. When comparing these results with the results obtained with the conventional values, it was concluded that the system would provide a more efficient alternative to the current method of water purification, thus, making it more economically sustainable.

Ennasri et al. [6] conducted a study to establish a reliable way to produce drinking water. Their focus was on desalination by RO using a system powered by solar energy. In their results, they concluded that the RO process does not include a phase change that must have a lower energy consumption than other separation processes, such as distillation. Furthermore, they emphasize that a better understanding of solar energy could improve their desalination system.

Delgado-Torres et al. [7] proposed an innovative hybrid desalination technology for maintainable off-grid systems by taking advantage of complementary features of tidal range and solar PV energies. Their findings were that for a given size of PV generator, the tidal range implies an increase in the operating time of the desalination system at a range of 1.8 to 2.8 times compared to when there is a solar PV only. They further discovered that the system could be operated at full load for 42 % of the year, thus increasing the yearly freshwater production.

Monjezia et al. [8] conducted research on the development of an off-grid powered RO desalination system with integrated photovoltaic thermal (PVT) cooling in Egypt. The results showed an increase in efficiency for PVT due to cooling and fewer required panels. They also found that there was an increase in RO efficiency due to high water viscosity. Furthermore, the results indicated that the method used led to a reduction of 0.12 kWh/m^3 in the specific electricity consumption rate of RO membrane desalination.

Lai et al. [9] investigated how the solar-powered RO seawater desalination system performance can be improved. Their results indicated that a novel self-diluted 2-stage RO process could improve the system's performance. They discovered that fresh water and stable salinity gradient energy can be produced simultaneously.

Sewaki and Chen [10] cost evaluated the two-staged RO process. Their evaluation was based on three types of two-staged RO, one without direct feed flow (hybrid A), one with direct flow feed flow (hybrid B), and one with direct feed flow and a turbine (hybrid C). They found that hybrid C was economically friendly because of its insensitiveness to electricity prices. Furthermore, the results showed that a two-staged RO improves the system's efficiency.

Rahimi et al. [11] conducted a study of solar-powered RO processes. Their study indicated that for discount rates higher than 23 % there is no room for PV-RO desalination plants. The study also showed that using energy recovery devices was not economically viable and further discovered that using batteries in the RO desalination was not a great idea.

Ghafoor et al. [12] discovered that membrane productivity increases by increasing feed water temperature. Their study was based on a RO plant with a capacity of 500 L/h, and results showed 60 % permeate productivity of the RO plant and 40 % brine solution.

Yuan et al. [13] conducted a performance evaluation of a co-production system of solar thermal power generation and seawater desalination. The evaluation confirmed that freshwater yield increases with feed water temperature.

Godart [14] working with the design and simulation of a heat-driven direct RO device for seawater desalination powered by solar thermal energy, designed and simulated a single-person portable desalination device. The author’s

findings were that the device can be built using off-the-shelf components and that the device could desalinate 5.98 L of 35 g NaCl/L seawater per day.

3. AIM, OBJECTIVE, AND SCOPE OF THE PRESENT WORK

The main aim of the current work was to explore an alternative way to produce freshwater for local communities around Durban. Cost is always a decisive factor for many projects, but the number of litres of fresh clean water produced is also relevant, considering that water is quite a problematic issue in KwaZulu-Natal. Hence, the objective of this work was to predict how many litres of water can be produced per year by this alternative way of producing fresh, clean water.

This research focused on research conducted in relation to a solar-powered RO seawater desalination system. The research first focused on what discoveries have been made about solar-powered RO seawater desalination over the years. The research further evaluated different designs that have been used in other countries over the years. In conclusion, a solution is proposed regarding design. This proposed solution is aimed at solving the shortage of water in Durban.

4. PREVIOUS DESIGNS OF SOLAR-POWERED RO DESALINATION SYSTEM

4.1 Design 1

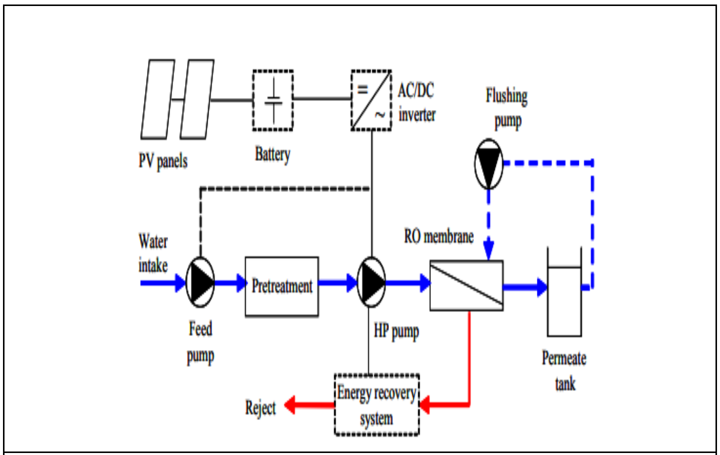


Figure 1: shows a Design by Ghermandi and Messalem [15].

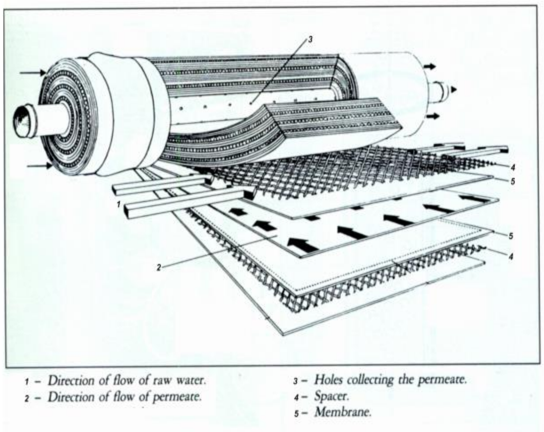


Figure 1: Schematic of Solar-Powered Figure 2. Spiral Wound RO Membrane [16] RO Desalination Process [15].

4.1.2 Description

High Pressure (HP) pump – to pump water with high force/pressure into RO membrane. Pretreatment system – To take out some of the unwanted substances in the feed water before it goes to the RO membrane. RO membrane (spiral-wound partially permeable membrane) – separate ions or unnecessary molecules or substances from the feed water. Consists of the main filter barrier, coarser filter and active carbon filtration. AC/DC inverter – AC induction motors require inverters to transform the DC current coming to the PV modules or stored in the battery. When DC motors are used, there is no need for inverters. Battery –Included as a back-up when there are cloudy weather conditions and at night. PV panels – To collect energy from the sun. Permeate tank – To store fresh water coming from the RO membrane.

4.2 Design 2

Figure 3 shows a design by Richards et l. [17].

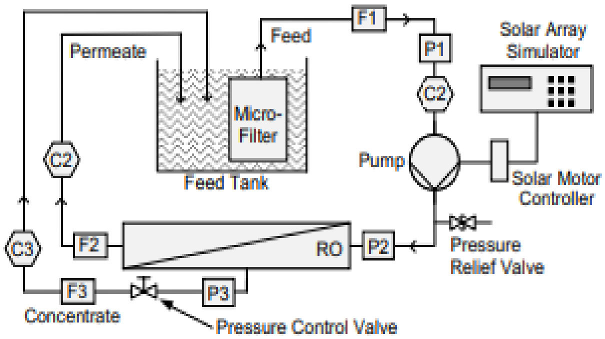


Figure 3: Schematic of the RO Membrane System [17].

4.2.1 Description

The system consists of three pressure sensors that detect pressure after the micro-filter, also before and after a single RO membrane module. Flowrates are found using turbine meters. To measure feed, stainless steel conductivity sensors are used. By using conversion factor k which is equal to 0.637 g.cm/L, electrical conductivity (mS/cm) is converted into NaCl concentration (g/L). This is identical to that captured using NaCl in deionized water at 15 °C. Two current and voltage sensors are used to capture power measurements. This is the power that is delivered by SAS and the power used by pump motor. Feedwater temperature and pH are detected using a thermocouple and a pH meter which are installed in the feed tank. [17].

Table 1: Items used in the System

Item	Type/Specification(s)
Pressure Sensor	Burkert, Model 8323
Turbine Meters	Omega, Model FTB9510 and Model FTB602B
Conductivity sensors (stainless steel)	GF Signet, Model 2821 and Model 2822
Current sensors	Omega, Model DRF-IDC
Voltage sensors	Omega, Model DRF-VDC
Thermocouple	Omega, Model 2717
pH meter	GF Instruments, Model KTSS-125G6

4.2.2 RESULTS

- **Magnitude** – Steps with a period of 15 min were supplied to the system in order to ensure that equilibrium had been reached. This was done to determine the effect that abrupt steps in the solar irradiance have on the RE-membrane system performance. The following equation was used for further analysis. [17]

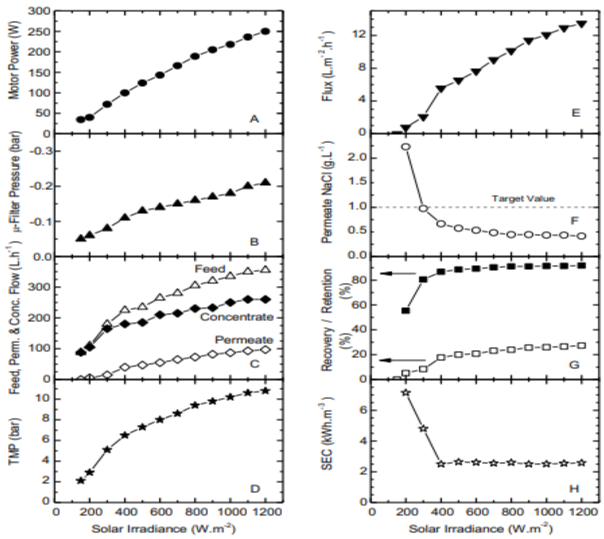
$$I_{on} = I_{off} + \Delta I \qquad (1)$$

- **On-time period** – The length of the off-periods (0 $W.m^{-2}$, 150 $W.m^{-2}$, 200 $W.m^{-2}$ and 300 $W.m^{-2}$) remained unchanged at 15 min, whereas the length of the on-period (400 $W.m^{-2}$) was changed with hope to change the duty cycle. This was done to bring understanding on how the RE-membrane react with shorter spikes in solar irradiance. The choosing of the on-periods was done such that the duty-cycle was defined as displayed in Equation 2 [17]:

$$\text{Duty} - \text{Cycle} = \frac{t_{on}}{t_{on}+t_{off}} \qquad (2)$$

where: 6 % is equivalent to 1 min, 25 % is equivalent to 5 min, 40 % is equivalent to 10 min, 50 % is equivalent to 15 min, 70 % is equivalent to 35 min, 90 % is equivalent to 135 min and 100 % is where there is no off period.

Results are shown in Figure 4 to Figure 10.



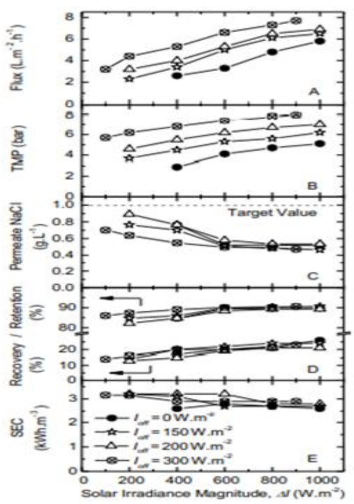


Figure 4: Graph of RO Membrane system's Performance vs the Constant Solar Irradiance Levels [17]. Figure 5: Graph Displaying Effect of Different Magnitudes of Solar Irradiance on the RE-Membrane System Performance. [17].

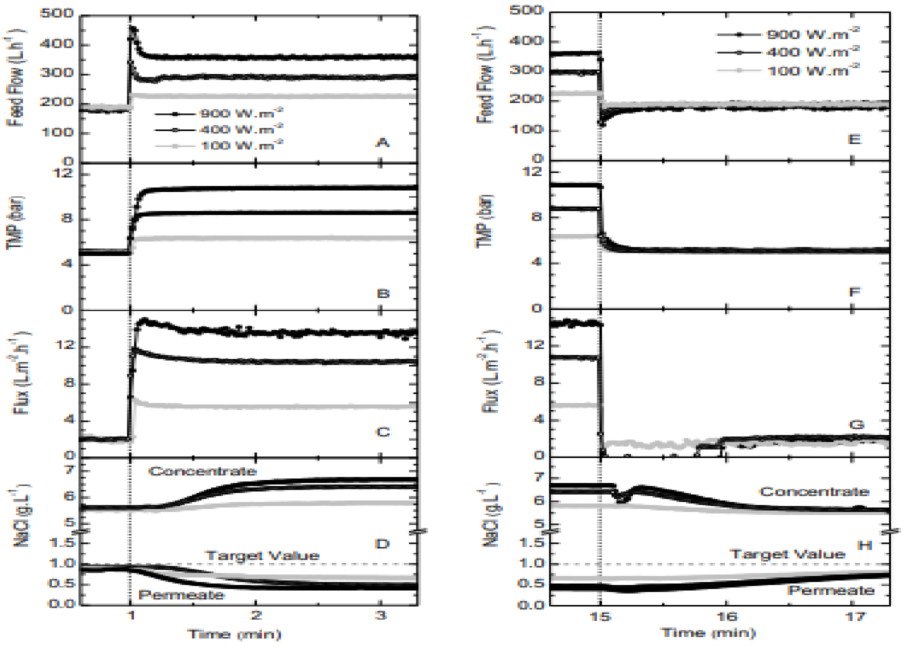


Figure 6: Graph Displaying the Effects of Three Different Magnitudes of Solar Irradiance Fluctuations from the Level of I_off [17].

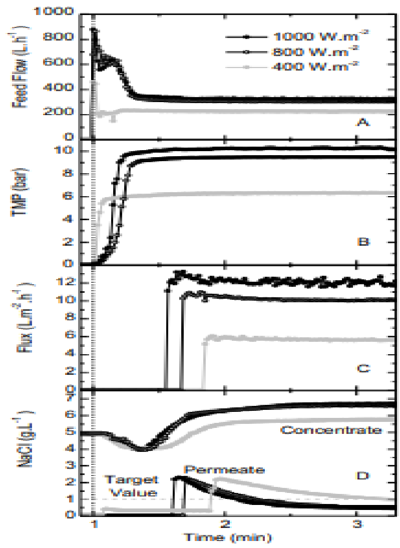


Figure 7: Graph Displaying the Effects of Three Magnitudes of Positive Solar Irradiance I_off [17].

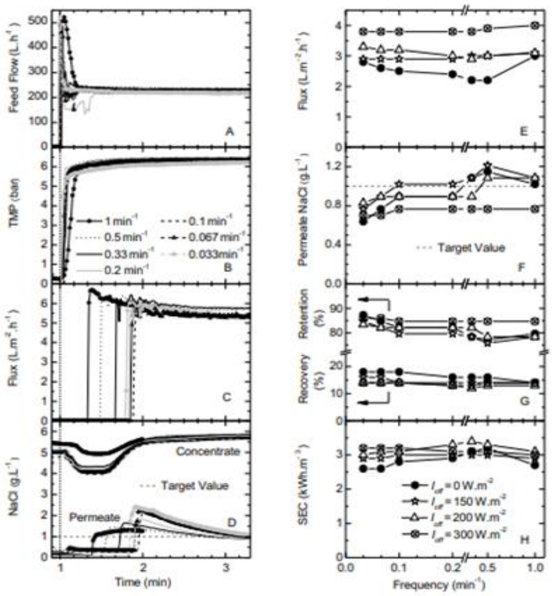


Figure 8: Graphs Displaying the Effects of the Different Magnitudes of Solar Irradiance Fluctuations from the Level of Ranging from 0 to 400 W.m-2 with Different Frequencies. [17].

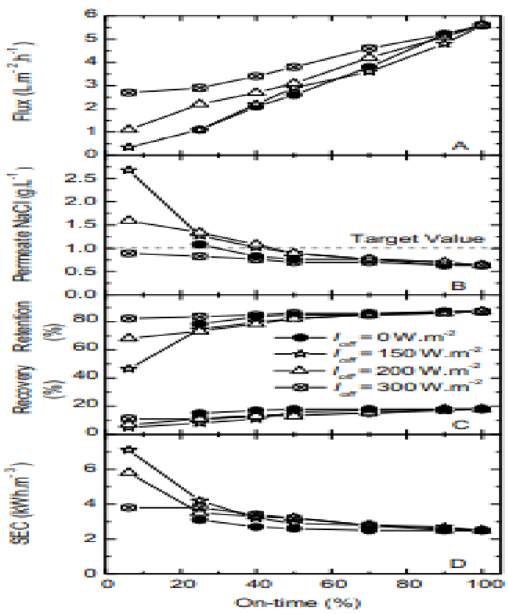


Figure 9: Graph Displaying the Effects of Solar Irradiance Fluctuations Magnitudes on the Performance of the RE-Membrane System Performance. [17].

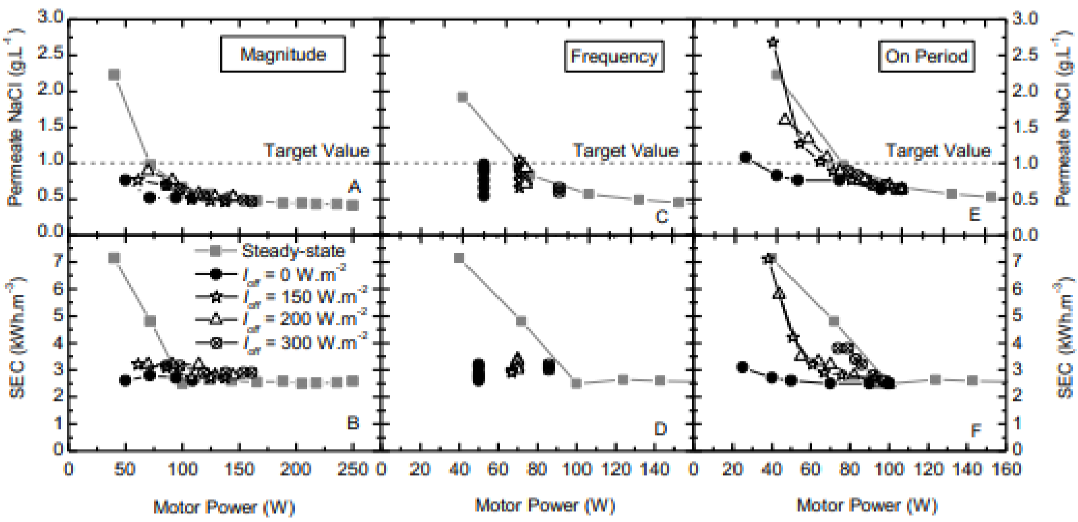


Figure 10: Graph Displaying Performance of the RE-Membrane System Performance under Different Solar Irradiance and under Constant Levels of Solar Irradiance. [17] .

4.3 Design 3

Figure 11 shows a design by Li et al. [18].

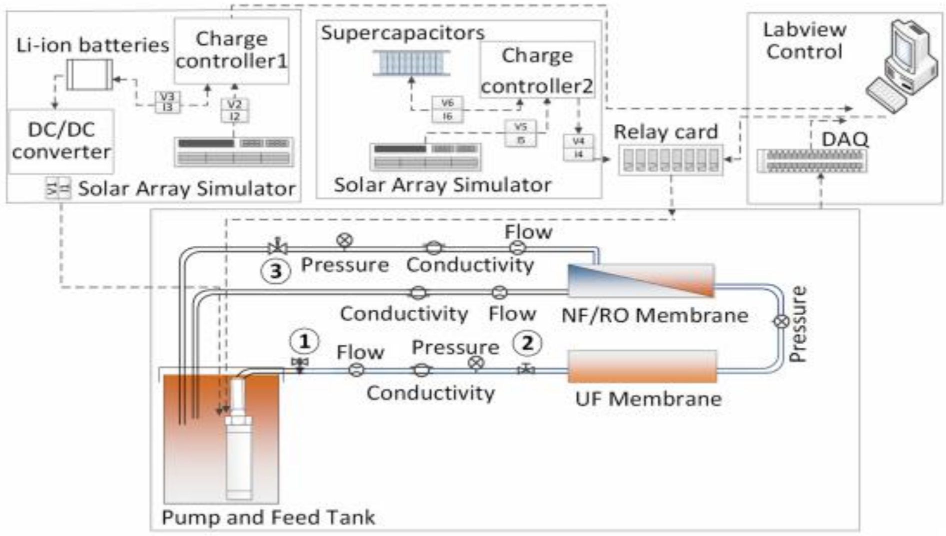


Figure 11: Schematic Diagram of Photovoltaic Membrane Equipped with a Lithium-Ion Battery Pack or Supercapacitors for Energy Storage [18]

4.3.1 Description

Two lithium-iron-phosphate (LiFePO4) battery packs (Power Brick 24 Vdc and 50 Ah, PowerTech Systems, France) are connected in parallel to provide a maximum battery capacity of 100 Ah for the PV-membrane system, for energy storage/supply. A charge controller (Victron MPPT 100/20, the Netherlands) is used to regulate the charging and discharging behaviours of the batteries with a maximum current up to 20 A. A DC/DC converter (MeanWell SD-500L-48, Taiwan) is used to convert the battery voltage from 24 Vdc up to 48 Vdc in order to supply a suitable voltage to drive the pump. Pairs of current (DRF-IDC, Omega, Bridgeport, N.J., USA) and voltage (DRF-VDC, Omega, Bridgeport, N.J., USA) sensors are installed to measure the electrical characteristics of both batteries and pump. These sensors are monitored to determine the status of the pump and batteries (charging or discharging). The other energy storage option was 12 SCs (Maxwell Boostcap BPAK0058-E015- B01; San Diego, California, USA) connected in a series to achieve a maximum output voltage of 180 V and a capacitance of 4.8 F. The charge controller design is based on pre-set voltage thresholds to control the state of the pump (on/off) and the charging/discharging behaviour. The switching of the energy storage options (Li-ion vs. SC vs. reference) is carried out manually. Inline sensors for measuring the pressure, flowrate, and EC are installed in feed, permeate and concentrate streams of the PV-membrane system to monitor instantaneous performances during transient periods. All the sensors exhibited a response time of 1 s or less, and their outputs are recorded using a data acquisition card (DAQ, National Instruments 6229; Austin, Texas, USA) and displayed instantaneously on a computer running LabVIEW for data logging and control. A needle valve in the concentrate stream is used to regulate the desired backpressure for the system. The feed water temperature is maintained at 20 °C ± 0.5 °C through a chiller [18].

4.3.2 Results

The membrane-specific parameters (flux, TMP, retention, recovery, and SEC) are calculated using well-known relationships, detailed in Equation 3 to Equation 7, and the results are shown in figure 12 [18].

$$J = \frac{Q_P}{A} \tag{3}$$

Where J = flux (L/m^2.h), A = membrane active area (m^2), and Q_P = permeate flowrate (L/h).

$$TMP = \frac{P_{inter-vessel} + P_C}{2} - P_{perm} \tag{4}$$

Where TMP = transmembrane pressure, $P_{inter-vessel}$ = pressure after the UF membrane (bar), P_C = pressure in the concentrate stream (bar), and P_{perm} = relative pressure of the permeate side (0 bar).

$$R = \left(1 - \frac{EC_P}{EC_F}\right) \times 100\% \tag{5}$$

Where R = recovery (%), EC_P and EC_F = electrical conductivity of permeate and feed (μS/cm).

$$Y = \left(\frac{Q_P}{Q_r}\right) \times 100\% \tag{6}$$

Where Y = recovery (%), Q_P and Q_F = flowrate of permeate and feed steam (L/h).

$$SEC = \frac{P_{pump}}{Q_P} \tag{7}$$

Where SEC = specific energy consumption (kWh/m^3), P_{pump}= electrical power of pump motor.

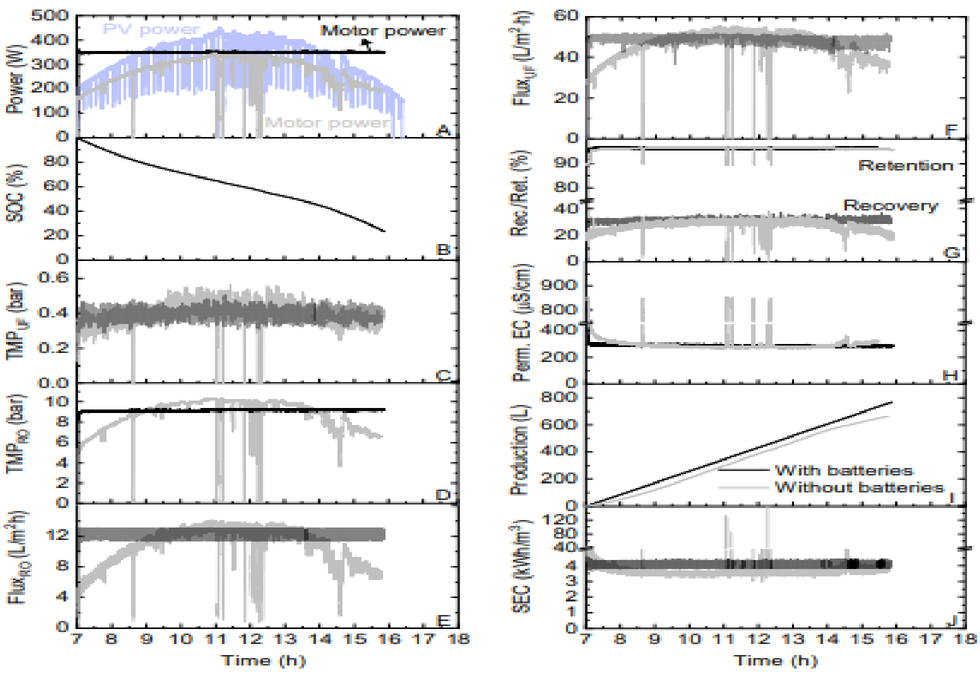


Figure 12: Performance of the PV-membrane system shown, firstly, with fully charged battery storage (100 % initial state-of-charge [SOC], black curves) and, secondly, the reference system without energy storage (grey curves) on the "partly cloudy day": (A) power, (B) SOC, (C) transmembrane pressure of UF membrane (TMPUF), (D) transmembrane pressure of RO membrane (TMPRO) (E) flux of RO membrane (fluxRO), (F) flux of UF membrane (fluxUF), (G) retention/recovery, (H) permeate electrical conductivity (EC), (I) production and (J) specific energy consumption (SEC) [18].

4.4 Design 4

Figure 13 shows a design by Hamza et al. [19].

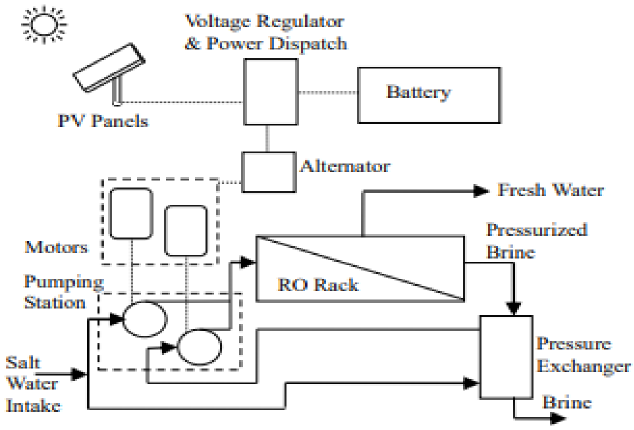


Figure 13: Schematic Diagram of Photovoltaic Powered RO Desalination System [19].

4.4.1 Description

Assuming salty water comes from an intake equipped with proper filtering. High pressure pumps deliver the salty water at a desired/design pressure value to the RO rack of pressure vessels. As the pressurized water flows through the membrane modules, a portion passes through the membranes and is collected into a low-pressure freshwater stream (product), while the rest exits as brine. To prevent the formation of an extremely high salinity boundary layer on the surfaces of the membranes, which can lead to membrane fouling, the salty stream is maintained at a highly turbulent flow state. As such, the exiting brine stream is typically still at high pressure and flow rate, which would constitute wasted energy if discharged. A pressure exchanger (PX) device is often included in RO desalination systems, which captures a good portion of the hydraulic energy in the exiting brine stream. Control systems govern the start-up, shut-down and pressure-regulation of the various streams. The modelling in this paper, however, does not encompass the details of the control systems, intake/filtering nor disposal of the discharged brine mainly due to the fact that these systems are well-documented off-the-shelf components, and their selection/operation is primarily a fixed cost (treated as an overhead) that do not depend on the design of the RO system. Since solar energy from photovoltaic panels is unavailable after sunset and can be highly variable throughout the day, an off-grid system requires battery storage to maintain steady operation. RO systems typically require around 4 hours of maintenance per day for back-washing the membrane modules, changing defective modules and other repairs. During the maintenance period, there is no production of freshwater, but the power draw of the desalination plant is significantly reduced. To take advantage of the typical daily power availability cycle, the maintenance period is assumed to happen between midnight and 4:00am every day. Aside from maintenance, the RO system has no hard restrictions on being run at partial load or even complete shutdown (in case of power unavailability) so long as: i) turbulence flow levels in the membrane modules are maintained to prevent fouling, and ii) change of state happens via a smooth ramp-up/down [19].

4.4.2 Results

<u>Cost estimation [19]:</u>

First-order cost models are used for estimation of investment costs of the hydraulic power components using Equation 8 to Equation 13 as follows:

$$C_{pump} = a_{0.pump} + a_{1.pump}x_4 \tag{8}$$

$$C_{px} = a_{0.px} + a_{1.px}x_1 f_5(x) \tag{9}$$

$$C_{motor} = a_{0.motor} + a_{1.motor}P_{max}(x) \tag{10}$$

Where a_0 and a_1 are constant and linear coefficients of the first-order cost models, respectively. $f_5(x)$ = exiting brine flow rate from a single vessel of the RO rack at nominal maximum flow rate and pressure conditions.

Initial investment cost of the RO rack of membrane modules (this includes pressure vessels, piping, valves, and controls) are estimated based on the number and type of modules used.

$$C_{rack} = x_1 x_2 c_{module}(x_3) \tag{11}$$

RO membrane modules require regular year-round replacements (with a replacement rate η_{rack} of 13 % to 15%).

$$\tilde{C}_{rack} = c_{rack}\,(1 + \eta_{rack} nROYears) \tag{12}$$

Battery costs are assumed proportional to the installed storage capacity. Since the battery storage is stationary, weight is neglected, and as such, the most cost economical values (corresponding to lead-acid batteries) are used:

$$_{Battery} = a_{1,battery}C_B(x) \tag{13}$$

The investment cost per installed nameplate DC power of the PV panels is estimated using the SAM 2012 simulations. The lifecycle of PV panels usually differs from the RO plant lifecycle (20 years to 30 years compared to 10 years). Thus, the effective yearly and daily costs are estimated using Equations 14 and Equation 15 as follows:

$$f_9(x) = \frac{C_{pv}}{nPVYears} + \frac{(C_{pump} + C_{motor} + \tilde{C}_{rack} + C_{battery} + C_{px}}{nROYears} \tag{14}$$

$$f_1(x) = \eta_{OH} f_5(x)/365 \tag{15}$$

Where $f_1(x)$ = equivalent cost per day of the whole system.

Where η_{OH} is a lumped overhead correction coefficient to account for installation, investment devaluation, as well as operation and maintenance costs [dimensionless] [19]. Table 1 and Table 2 show the design variables and cost estimation coefficients.

Table 2: Summary of Design Variables [19]

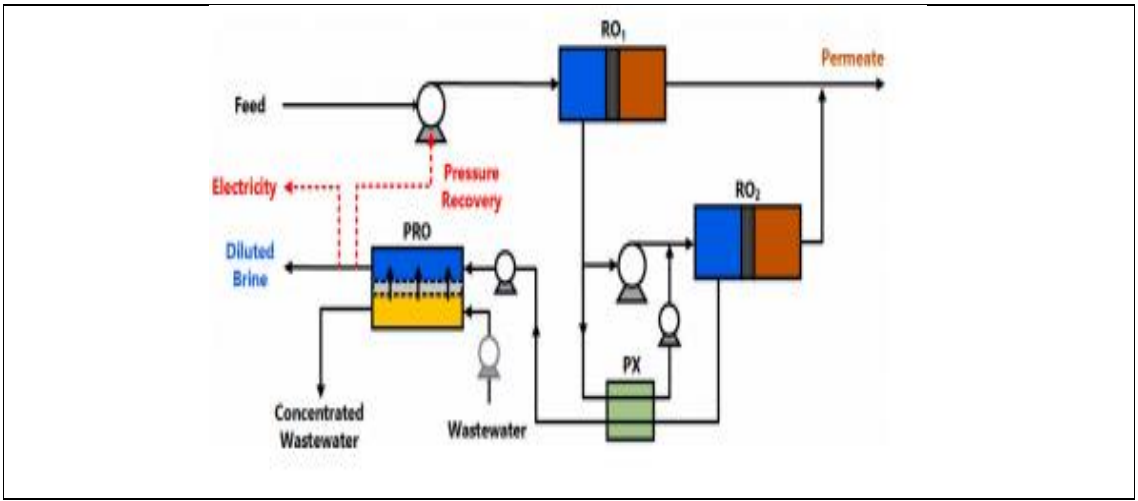
Var.	Description	Type	Units
x_1	Number of pressure vessels in RO rack	Discrete	Dimen-sionless
x_2	Number of RO membrane modules per pressure vessel	Discrete	Dimen-sionless
x_3	Selected RO membrane module type from catalogued list	Discrete	Dimen-sionless
x_4	Nominal salty water intake flow rate	Continuous	m^3/hr
x_5	Nominal operating pressure for the high-pressure pumps	Continuous	bar

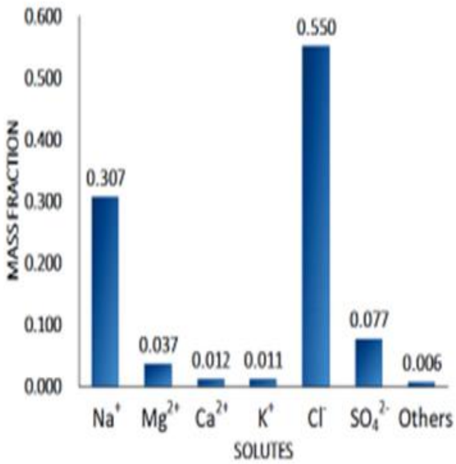
Table 3: Cost Estimation Coefficients [19]

Coefficient	Value	Unit
$a_{o,pump}$	75,000.00	$
$a_{1,pump}$	375.00	$/($m^3$/hr)
$a_{o,px}$	40,000.00	$
$a_{1,px}$	400.00	$/($m^3$/hr)
$a_{o,motor}$	25,000.00	$
$a_{1,motor}$	125.00	$/kW
$a_{1,battery}$	170.00	$/kW.hr
η_{OH}	1.30	Dimensionless

4.5 Design 5

Figure 14 shows a design by Sawaki and Chen [20]. Figure 15 shows sea salt composition of the seawater used in the study.





PX – pressure exchanger
RO-RO Membrane
PRO – pressure-retarded osmosis

Figure 14: Schematic Diagram of a Two-Staged Figure 15: Properties of Sea Salt RO and Pressure Retarded Osmosis Desalination Composition [20] Process [20].

Specific energy consumption for a single-staged RO process is calculated with Equation 16.

$$SEC = \frac{W_{hp}}{F_P} = \frac{P_{op}F_f}{\eta_{hp}F_P} \quad (16)$$

Where SEC = specific energy consumption, W_{hp} = power consumption of a high-pressure pump, η_{hp} = efficiency off the pump, P_{op} = operating pressure of the feed, and F_f and F_P = volumetric flow rates of the feed and permeate [20].

4.6 Design 6

Figure 16 shows a design by Amin et al. [21].

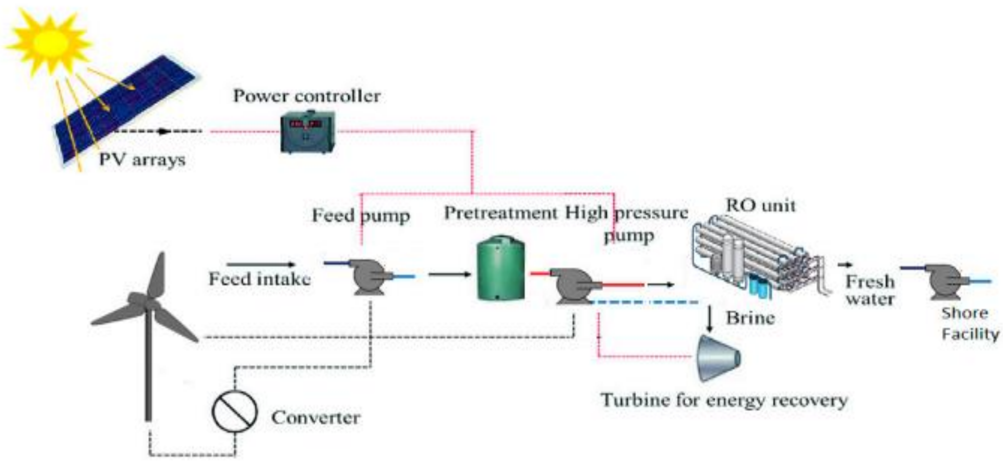


Figure 16: Schematic Diagram of the Solar-Wind-Driven Desalination System [21].

Power inverters are used to control and integrate the solar-wind system, thus, the controlling system controls the solar-PV and wind turbine systems. By definition, the hybrid system is an off-grid energy generation system in the form of

electricity and fresh water. Both of these products are collecting renewable resources from the sun, wind, and sea. The operation of pumping freshwater to a shore facility is done by using pressure pumps installed at the top of each tank. [21].

4.6.1 Results

The overall power consumption of a single RO module was found using the WAVE simulation program. The overall power for RO modules in the system was found to be 1591.2 kWh. The value of 483.9 kW was found to be the peak power of a single module that does not a power recovery system. For marine operation and the accommodation of power loads, the maximum power consumption was found to be 1660 kWh. This is for power consumption of operating pumps, lighting and control, and outfitting devices as displayed in Table 4. [21]

Table 4: Power Consumption of each RO Module per Hour [21]

No	ITEM	Flowrate (m^3/h)	Head (bar)	Efficiency (%)	ABSORBED POWER (KW)	QTY	TOTAL ABSORBED POWER (KW)
01	Filter feed pumps	226	5	78	40	6	240
02	high pressure pumps	86	65.5	78	200	6	1200
03	High pressure booster pumps	128	3	78	14	6	84
04	cleaning and flushing pumps	210	4	78	30	2	60
05	Coagulant				0.3	6	1.8
06	Antiscalant				0.3	6	1.8
07	Post pH adjustment				0.3	6	1.8
08	Post chlorination				0.3	6	1.8
						Total	1591.2

5. DESIGN OF A SOLAR POWERED REVERSE OSMOSIS DESALINATION SYSTEM

A Case Study for Durban

Figure 17 shows the solar powered RO system investigated in the current study.

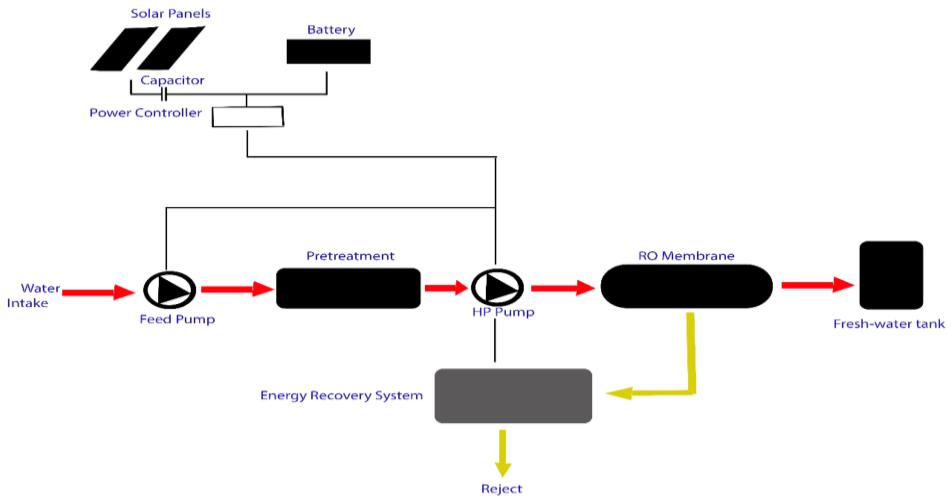


Figure 17: Schematic Diagram of a Solar Powered RO Seawater Desalination System.

5.1 Description

The design is a small project with an aim to produce a minimum of half a tank to a full tank (2400L tank) of fresh water per day with favourable weather conditions (sunny days). As shown in Figure 17, seawater is collected at water intake by

the feed pump (Speroni Single Stage Flanged Pump- 3kW [22]). Feedwater driven by the feed pump enters into the pre-treatment system, then is pumped by the high pressure (HP) pump (multi-stage HP pump of KSB Multitec-RO series [23]) into the RO membrane (same as the one in Figure 2). The DC motors are used in order to avoid energy losses compared to when using AC motors. There are two DC motors that drive the pumps; one drives the feed pump and the other drives the HP pump. RO membrane is a spiral wound RO membrane (see Figure 2). Water from the pretreatment system is pumped with high/full force/pressure into the RO membrane. In the RO membrane, with the help of the HP pump, fresh clean water goes into the tank and the waste is removed from the feed water and goes into the energy recovery system. In the energy recovery system, hydraulic motors are used. For energy supply/storage, the system is solar driven (with 20 PV panels from [24]), but when the weather does not favour solar panels and at night, battery (Vision 12V Lithium-Ion Battery 200Ah [LiFePO4] [25]) and the capacitor are there to provide energy. Durban is a sunny location; thus, Durban is the right place for solar energy projects.

5.2 Calculations

5.2.1 System Performance

In every design, there must be an estimate or prediction of how the design will perform in the future, in order to improve the design before it is manufactured. Equations 17 to Equation 25 help to predict the average daily freshwater production.

$$f_3(x) = \frac{x_4}{x_1} \tag{17}$$

where $f_3(x)$ is the inlet seawater flow rate into a single pressure of the pre-treatment.

$$f_{10}(x) = \frac{x_{11}}{x_{10}}$$

where $f_{10}(x)$ is the feedwater flow rate (water from the pre-treatment system into the RO membrane) into a single pressure of the RO membrane.

$$P_{max}(x) = \frac{1}{\eta_p} x_4 x_5 - \eta_r x_1 f_5(x) f_8(x) \tag{18}$$

where $P_{max}(x)$ is the full load operating power of the RO system.

$$P_{PVN}(x) = x_6 P_{max}(x)$$

where $P_{PVN}(x)$ is the nameplate DC power of the PV panels. 19)

$$C_B(x) = x_7 P_{\max}(x)$$

20)

$$P_{RO}(t) = y(t) P_{max}(x) \tag{21}$$

$$y(t) = x_8 z(t) + x_9 \dot{z}(t) \tag{22}$$

where $C_B(x)$ is the storage capacity [kW.hr], $P_{RO}(t)$ is the power at which the RO system is operated at time t [kW], y(t) is the fraction of $P_{max}(x)$ at which the RO system is operated at time t [dimensionless], z(t) is the battery state of charge as a fraction as the battery energy storage capacity [dimensionless], and $\dot{z}(t)$ is the derivative of z(t) with respect to time.

The following equation is used to calculate the power dispatched into the RO system.

$$z(t+1)=\begin{cases} z(t)-\frac{P_{RO}(t)-P_{PV}(P_{PVN}(x),t)}{C_B} \; if \; P_{RO}>P_{PV} \\ z(t)+\frac{\eta_B(P_{PV}(P_{PVN}(x),t))-P_{RO}(t))}{C_B} \; otherwise \end{cases} \tag{23)}$$

Where t is the start of the year [hr], $P_{PV}(P_{PVN}(x),t)$ is the estimated average harvested power by the PV panels at time t [kW].

$$n_v(t)=Round\,(\frac{y(t)x_4}{f_3(x)}) \tag{24)}$$

$$p_{in}(t)=\begin{cases}\left(\frac{n_v(t)P_{max}(x)}{x_1P_{RO}(t)}\right)x_5 \; if \; \frac{n_v(t)P_{max}(x)}{x_1P_{RO}(t)}\le 1 \\ x_5 \; otherwise\end{cases} \tag{25}$$

where $p_{in}(t)$ is the instantaneous inlet feed water pressure to the pressure vessel [bar].

The average daily freshwater production is estimated by averaging over the hours in one complete year (see Equation 26).

$$f_2(x)=\frac{1}{h}\sum_{i=1}^{h} n_v(t)f_7(t) \tag{26)}$$

Where h represents yearly hours when the RO system is functioning [19].

5.2.2 Sample Calculation

To determine or estimate the performance of the design, the following specifications about the system have to be used. Table 4 displays the specifications pertaining to system performance calculations.

Table 5: Specifications Pertaining System Performance Calculations

Spec.	Source	Value
x_1	Assumed	4
x_4	[23]	850 m^3/hr
x_5	[23]	8.8 MPa
RO System Power	[23] [22] [26]	6 kW
PV Panel Power $P_{\max 1}$	[24]	6.6 kW
Battery Storage $P_{\max 2}$	[25]	2.4 kW
x_6	Calculated	1.1
x_7	Calculated	0.4
q_{out}	Assumed	400 m^3/hr
$f_7(x)$	Assumed in ref. to x_4	850 m^3/hr
$f_8(x)$	$f_8(x)$ = p_{in} [19]	7 MPa
n_v	Assumed	5
h	Assumed	12 hours per day in winter. 8 hours per day in summer/spring/autumn. Thus, h = (8 x 30 x 3) + (12 x 30 x 9) = 3 960 operating hours per year

$f_3(x) = \frac{x_4}{x_1} = \frac{850}{4} = 212.5\ m^3/\mathrm{hr}$

$f_5(x) = \frac{q_{out}}{x_1} = \frac{7}{4} = 2.5\ MPa$

$P_{PVN}(x) = x_6 P_{\max 1} = (1.1)(6.6) = 7.26\ kW.hr$

$C_B(x) = x_7 P_{\max 2} = (0.4)(2.4) = 0.96\ kW.hr$

$f_2(x) = \frac{1}{h}\sum_{t=1}^{h} n_v(t) f_7(t) = (3960)(5)(850) = 16\ 830\ 000\ m^3 = 16.83\ Ml$

Therefore, with this system, an amount of 16.83 megalitres can be expected to be produced per year if the weather behaves as accounted for when operating hours per year were calculated. That is 46 109 L per day on average. This means that the equivalent of about 3 200 JoJo Tanks (5 250L) can be filled within a year by this system.

6. CONCLUSIONS

The main finding of this research was that with solar-powered RO seawater desalination, tons of fresh clean water can be produced if cost is not a crucial factor. The proposed design is a design without too much consideration of cost but is focused on the number of litres that can be produced. The proposed design uses PV panels that can absorb 6.6 kW of solar energy, with the entire system using 6 kW of power. The system can produce 16 830 000 litres of water per year when the system is operated for 3 960 hours in that year. This is a good amount of fresh water that can be used by the Durban community as an alternative when there is a shortage of daily water for essential use. Hence, the aim and objectives of this research were met.

Seawater desalination by RO proves to be one of the best options in producing freshwater. A two-stage RO can improve the system's performance, hence, increasing freshwater productivity. This research showed that the RO seawater desalination can be portable. In terms of cost, solar energy made the RO desalination more economically friendly. Researchers are still researching ways to make RO seawater desalination powered by solar energy more cost-effective so that other countries can afford it. The solar-powered RO seawater desalination can also have three power supplies (solar panels, battery, and wind-powered) to increase freshwater production per annum.

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